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STUDY OF SOME ASPECTS OF REACTION CROSS-SECTION BETWEEN DEFORMED NUCLEI

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ABSTRACT

The reaction cross-section is calculated for three deformed-deformed interacting pairs at range of energy [100-1000 MeV] per nucleon taking into account three approaches of the density dependence of the nucleon-nucleon reaction cross-section, the energy and orientation dependence of the reaction cross-section are studied. We found that, the reaction cross-section σ_R is strongly orientation dependent for the three deformed-deformed interacting pairs. The percentage ratio between the minimum and maximum values of σ_R changes up to 80% for the energy range considered.

KEYWORDS: Deformed-Deformed Interacting Pairs, Glauber Theory, Nucleon-Nucleon Interaction

INTRODUCTION

The optical limit to Glauber theory is usually used with appreciable success to describe the reaction cross section between complex nuclei [1-3]. The inputs to these calculations are the nucleon- nucleon (NN) reaction cross-section, σ_{NN}, and the density distribution of the interacting nuclei. Recently, this method has been used to determine the rms radii of the interacting nuclei and to study halo nuclei [2-5]. The value of σ_R for a pair of interacting nuclei calculated in the frame work of the optical limit of Glauber theory is affected by different factors. One of these factors is the method of treating in-medium effects. Also, it is sensitive to the range of the NN force. σ_R is usually calculated by assuming the zero-rang force [2] of the interacting nucleons and the NN reaction cross-section is considered through different approaches [5,6]. This approach in treating in-medium effects permits extracting σ_{NN} out of integrations since; in this case, it has constant value. Moreover for constant value of σ_{NN} and assuming Gaussian shapes for the density distribution, most of the integrals in calculating σ_R can be performed analytically which means that the evaluation of σ_R is numerically very simple.

The in-medium effects in NN cross section [7-10] at low and intermediate energies is due to Pauli blocking, which prevents the scattered nucleons to go into occupied states in binary collisions between the projectile and target nucleons. The accurate treatment of in-medium effects is the geometric approach of Pauli blocking which needs numerical calculations of fivefold integral to get σ_{NN}. Due to this complexity, many authors simplified this effect by assuming different approximations [7-10]. Recent expression for σ_{NN} was derived in Ref. [5] which takes in-medium effects through density and energy dependence in σ_{NN}. When $\sigma_{NN}(\rho)$ is determined from local matter density in each volume element of the nuclear overlap region, the value of σ_R is reduced by few percent compared with that obtained using free NN cross section σ^f_{NN} [7,11]. This is because the constant effective global density ρ in σ_{NN} which produces the same value of σ_R as the more complicated correct treatment of density dependence is too small compared to the saturation nuclear matter density $\rho = 0.17\ \mathrm{fm}^{-3}$ [5]. Since the calculated value of σ_R is affected by several factors like the method of treating in-medium effects and range of NN force, it is needed to study the variation of σ_R with these factors.

The aim of the present work is to study the variation of the reaction cross-section at low and intermediate energies with different approaches of considering in-medium effects of σ_R

In this work the optical limit of the Glauber theory is used to calculate the reaction cross-section, σ_R of the deformed-deformed interacting pairs (^{17}N-^{17}N), (^{17}N-^{238}U) and (^{238}U-^{238}U) for different orientations of the symmetry axes of the deformed nuclei. Both the energy and orientation dependencies of the reaction cross-section are studied.

METHOD OF CALCULATIONS

We have performed the calculations of the reaction cross-sectionas,

$$\sigma_R(\beta_P,\beta_T,\Omega_T,\Omega_P,E_L/A_P) = 2\pi\int b\,db\left\{1-T(b,\Omega_T,\Omega_P,E_L/A_P)\right\} \quad (1)$$

at $E_L/A_P = 100\ MeV$ per nucleon.Wherethe transparency of the collision is calculated from,

$$T(b,\Omega_T,\Omega_P,E_L/A_P) = \exp\left(-\chi'(b,\Omega_T,\Omega_P,E_L/A_P)\right) \quad (2)$$

$$\bar{\sigma}_{NN}(\rho,E_L/A_P) = \frac{N_P N_T \sigma_{nn} + Z_P Z_T \sigma_{pp} + N_P Z_T \sigma_{np} + N_T Z_P \sigma_{np}}{A_P A_T} \quad (3)$$

$A_P, N_P\ and\ Z_P\left(A_T, N_T\ and\ Z_T\right)$ are the projectile(target) mass, neutron, and proton numbers, respectively. $\sigma_{nn}\left(=\sigma_{pp}\right)$ and σ_{np} are the neutron-neutron (= proton-proton) and neutron-proton reaction cross-section, respectively, and they are given by [11,12, 13],

$$\sigma_{nn} = \sigma_{pp} = \left(13.73-15.04\beta^{-1}+8.76\beta^{-2}+68.67\beta^{4}\right)\times\left[\frac{1+7.772\left(E_L/A_P\right)^{0.06}\rho^{1.48}}{1+18.01\rho^{1.46}}\right], \quad (4)$$

$$\sigma_{np} = \left(-70.67-18.18\beta^{-1}+25.26\beta^{-2}+113.85\beta\right)\times\left[\frac{1+20.88\left(E_L/A_P\right)^{0.04}\rho^{2.02}}{1+35.86\rho^{1.9}}\right], \quad (5)$$

where, $\beta = \sqrt{1-\frac{1}{\gamma^2}}$ is the ratio of the projectile speed to the light speed and

$$\gamma = 1+\frac{\left(E_L/A_P\right)}{931.5}.$$

We assume zero range nucleon-nucleon interaction.Different orientations, for the symmetryaxes of the projectile and the target(Ω_P,Ω_T), $\theta_P,\ \theta_T = 0^o,\ 45^o,\ 90^o$ and $\phi_P,\ \phi_T = 0^o,\ 30^o,\ 45^o, 60^o, 90^o$ are considered. We study the effect of the in-medium NN interaction on the reaction cross-section by considering three different approaches for evaluating the NN reaction cross-section $\bar{\sigma}_{NN}(\rho,E_L/A_P)$by three different approaches in evaluating the total nucleon-nucleon reaction cross-section. The first one, implement the free interaction (ρ = 0 fm^{-3}), the second approach, is to take constant value for the nuclear density (ρ = 0.16 fm^{-3}), and the third one considers the exact value of the local densityρ taken as the sum of the projectile and the target densities, finally, these calculations are compared with each other.

The present study is done on the interaction of the light pair (^{17}N-^{17}N), the light-heavy pair (^{17}N-^{238}U) and the heavy interacting pair (^{238}U-^{238}U). For each interacting nuclear pair, we determined the orientations of the nuclei symmetry axes corresponding to the maximum and the minimum values of the reaction cross-section. Moreover, we calculated σ_R^{ss} for each interacting pair defined as the reaction cross-section of the equivalent spherical nuclei with r.m.s. radii equal to the corresponding r.m.s. radii of the deformed nuclei. For the equivalent spherical nucleus, its density is given by,

$$\rho^s(r) = \rho_0^s\left[1+\exp\left(\frac{r-R_0^s}{a}\right)\right]^{-1}$$

where, ρ_0^s can be calculated from, $4\pi\int \rho^s(r) r^2\, dr = A \quad (mass\ number)$

and, R_0^s is obtained from, $\int \rho^s(r) r^2\, dr = \int \rho^d(r,\theta) r^2\, d\bar{r}$

where, $\rho^d(r,\theta)$ is the density distribution of the deformed nucleus.

Table 1: The Reaction Cross-Section of the Equivalent Spherical Nuclei, σ_R^{ss}

	^{17}**N**	^{238}**U**
ρ_0^s	0.246078	0.167427
R_0^s	2.670412	5.723379

	(^{17}N-^{17}N)	**(^{17}N-^{238}U)**	**(^{238}U-^{238}U)**
σ_R^{ss} fm^2	185. 9	373.0	628.3

We consider quadrupole deformation parameter in the density distribution of the deformed nuclei and assume the absence of higher order deformation parameters.The ingredients needed to perform numerical calculations of Eq. (1) are the parameters associated with the two interacting nuclei (^{17}N and ^{238}U), which are, A_P (A_T), N_P (N_T), Z_P (Z_T), ρ_{P0} (ρ_{T0}), R_{P0} (R_{T0}), a_P (a_T), and β_{P2} (β_{T2}) of the projectile (target) and all given in Table (1).

RESULTS AND DISCUSSIONS

The values obtained for the reaction cross-section of (^{17}N-^{17}N), (^{17}N-^{238}U) and (^{238}U-^{238}U) interacting pairs at $\theta_P, \theta_T = 0^o, 45^o, 90^o$ and $\phi_P, \phi_T = 0^o, 30^o, 45^o, 60^o, 90^o$ are shown in Table (2). In this table, we used $\rho = \rho_P + \rho_T$ to evaluate the nucleon-nucleon (NN) reaction cross-section. This is done by permitting ρ_P *and* ρ_T to vary in each volume element during the integration process. Another two approaches can be used to simplify the density dependence of $\bar{\sigma}_{NN}$, one is to assume free NN interaction and the other is to assume constant global density value ($\rho = 0.16\ fm^{-3}$) in evaluating $\bar{\sigma}_{NN}$. Table (2) shows that, for two coplanar symmetry axes ($\phi_P = \phi_T = 0^o$) and when $\theta_P = 0^o$, the value of the reaction cross-section increases by increasing the value of θ_T. In this case the reaction cross-section σ_R for (^{17}N-^{238}U) increases by about 20.3% and 36.6%, compared to its value at $\theta_T = 0^o$, when the target symmetry axis is oriented by 45^o and 90^o respectively. This increase in σ_R is reduced to 13.6% and 23.5% for (^{238}U-

^{238}U) pair and becomes 5.3% and 10.3% for (^{17}N-^{17}N) pair. At $\theta_T = 45^o$, the light projectile ^{17}N in the pair (^{17}N-^{238}U) when it is oriented by 45^o, the reaction cross-section increases by only 2.8%. Small increase in the reaction cross-section is produced at $\theta_T = 90^o$ by orienting ^{17}N nucleus from 0^o to 90^o (5.1%). This means that in the light-heavy pair, the orientation of the heavy nucleus produces strong variation in the reaction cross-section while the light one appears as spherical. This means that the orientation dependence of the reaction cross-section for two coplanar symmetry axes is too strong for the light-heavy pair (^{17}N-^{238}U) and too weak for the pair (^{17}N-^{17}N).

Concerning non coplanar symmetry axes, Table (2) shows the reaction cross-section for the three interacting pairs when the azimuthal angles are different from zero. For $\theta_P = \phi_P = 0^o$ and $\theta_T = 90^o$, the reaction cross-section for the light-heavy interacting pair (^{17}N-^{238}U), decreases by percentages 7.4%, 14.7% and 29.1% when the target azimuthal angle, ϕ_T, changes from $\phi_T = 0^o$ to 30^o, 45^o and 90^o respectively. For light-light and heavy-heavy pairs, this decrease is respectively (2.7%, 5.4% and 10.7%) and (4.4%, 9.3% and 20.3%) in the same range of ϕ_T variation. This means that the heavy-light pair reaction cross-section has strong ϕ_T dependence compared to the other two pairs. At $\theta_P = \phi_P = 0^o$ and $\theta_T = 45^o$, the reaction cross-section for the pairs (^{17}N-^{238}U), (^{17}N-^{17}N) and (^{238}U-^{238}U) decrease by percentages 13.6%, 4.3% and 9.3% respectively when ϕ_T changes by 60^o.

The reaction cross-section of the interacting light-heavy pair (^{17}N-^{238}U) , for $\theta_P = \theta_T = 90^o$, decreases by 4% and 5% with increasing ϕ_P by 60^o at $\phi_T = 0^o$ and $\phi_T = 60^o$ respectively, also σ_R decreases, by nearly 21.7%, for increasing the orientation of ϕ_T, from 0^o to 60^o, at constant ϕ_P. This means that, for the pair (^{17}N-^{238}U), the orientation dependence of σ_R on ϕ_T is more significant than its dependence on ϕ_P. The other two reactions contain equal mass number of the interacting nuclei. So, for these reactions the orientation dependence of σ_R on ϕ_P is the same as ϕ_T. Also the dependence of σ_R on both θ_P *and* θ_T is the same.

For the heavy (^{238}U-^{238}U) pair, for $\theta_P = \theta_T = 90^o$, σ_R decreases by about 6.5% and 11% when ϕ_P increases to 60^o and 90^o respectively, or the dependence on ϕ_P increases when the volume increased. The calculations are decreased, by nearly 6.5%, 15% and 14.3%, for increasing the orientation of ϕ_T from 0^o to 60^o, at $\phi_P = 0^o, 60^o, 90^o$ respectively.

Finally, at $\theta_P = \theta_T = 90^o$, for light ($^{17}N$-$^{17}N$) pair, σ_R decreases by about 7.6% and 10.1% when ϕ_P increased to 60^o and 90^o respectively. Noted that, the dependence of σ_R, for (^{17}N-^{17}N) pair, on ϕ_P is the same as (^{238}U-^{238}U) pair, because that the target and the projectile are identical. Also the reaction cross-section of the light-light pair, (^{17}N-^{17}N), is decreases, by nearly 7.6%, 8.2% and 7.9%, for increasing the orientation of ϕ_T, from 0^o to 60^o, at $\phi_P = 0^o, 60^o, 90^o$ respectively.

The calculations of σ_R for the interacting light-heavy pair (^{17}N-^{238}U), at $\theta_P = \theta_T = 45^o$, $\phi_P, \phi_T = 0^o, 30^o, 45^o, 90^o$ are listed also in Table (2). At $\phi_P = 0^o$, the calculations are shown to be decreased, by 4.4%, 8.9% and 18% with increasing ϕ_T, from 0^o to 30^o, 45^o and 90^o respectively. But, at $\phi_T = 0^o$, the results are shown to be decreased, by 0.75%, 1.5% and 3% when ϕ_P increases from 0^o to 30^o, 45^o, and 90^o respectively. It is clear that, the reaction cross-section of (^{17}N-^{238}U) pair is strongly dependent on the azimuthal angle, ϕ_T of the target and slightly depends on the azimuthal angle, ϕ_P of the projectile. This is because, the volume of the projectile is small compared to the target.

The maximum value of the reaction cross-section occurring for all possible orientations of the symmetry axes of both target and projectile is at $\theta_P = \theta_T = 90^o$ and $\phi_P = \phi_T = 0^o$. The corresponding minimum value σ_R occurs for the orientation $\theta_P = \theta_T = \phi_P = \phi_T = 90^o$. Their values at energy per projectile nucleon $E_L / A_P = 100\ MeV$ are given in Table (2). The percentage differences to the average between the two values are 21.7%, 39.2% and 33.7% for (^{17}N-^{17}N), (^{17}N-^{238}U) and (^{238}U-^{238}U) reactions respectively.By simple comparison between Table (1) and Table (2), one can see that, the reaction cross-section of the equivalent spherical nuclei, σ_R^{ss} for the light pair has a value larger than the maximum value of the deformed-deformed reaction cross-section. While, for (^{17}N-^{238}U) it has a value in between the maximum and the minimum value of σ_R in the case of the deformed nuclei. And for the heavy pair it has a value less than the minimum one of the deformed σ_R. All of these are due to the effect of the deformation of nuclei, which is very important to study.The maximum and minimum values of the reaction cross-section, σ_R at different values of E_L / A_P are given in Table (3) for the three considered reaction processes (^{17}N-^{17}N), (^{17}N-^{238}U) and (^{238}U-^{238}U). For these interacting pairs, one can see that, the percentage ratio between the minimum and the maximum values of σ_R for different values of energy is almost constant and have the values 80%, 67% and 70% respectively.

Figures (1a, 1b, and 1c) show the variation of $\sigma_R^{\max.}$ and $\sigma_R^{\min.}$ with the value of E_L / A_P for the three reactions respectively. The reaction cross-section for the three reactions have the same behavior with E_L / A_P and each cross-section, has minimum value at $E_L / A_P \cong 250\ MeV$ then the curves increase slowly as the value of E_L / A_P increases. The behavior of σ_R with the energy is due to the energy dependence in the NN cross-section $\bar{\sigma}_{NN}(\rho, E_L / A_P)$. The energy variation of σ_R for two deformed nuclei is similar to the case of their equivalent two spherical nuclei. Figure (2), shows the dependence of σ_R on ϕ_T for the interacting pair (^{17}N-^{238}U). The reaction cross-section is independent of ϕ_T if $\theta_T = 0^o$, but it has a very significant dependence on the azimuthal angle, ϕ_T of the target if $\theta_T = 90^o$. Also in this figure, the reaction cross-section σ_R was decreased by nearly 6.25% after we increased the azimuthal angle ϕ_P of the projectile by 90^{o}if $\theta_T = 0^o$, and by nearly 5% if $\theta_T = 90^o$.

We now show the effect of the in-medium NN interaction on σ_R by considering two types of NN interaction. The first assumes that the two interacting nucleons are imbedded in constant nuclear matter with density value

$\rho = 0.16\ fm^{-3}$ and evaluate $\bar{\sigma}_{NN}(\rho, E_L / A_P)$ at this constant global density. The second type is the interaction between two free nucleons where we neglect the effect of surrounding medium and evaluate $\bar{\sigma}_{NN}(\rho, E_L / A_P)$at $\rho = 0\ fm^{-3}$. Referring to Table (4), we obtained the effects of the in-medium NN interaction on the reaction cross-section of the interacting pairs (^{17}N-^{17}N), (^{17}N-^{238}U) and (^{238}U-^{238}U) at $\rho = 0\ fm^{-3}$, $\rho = 0.16\ fm^{-3}$ and $\rho = \rho_P + \rho_T$ .We can summarize this effect as follow:

- When the exact value of the density is considered during the integration process, the difference between the values of the reaction cross sections and thoseevaluated using the free NN cross section $\rho = 0\ fm^{-3}$ is significant, for our three reactions, the reaction cross-section increased by nearly **5 fm^2,** except for the interacting pair (^{238}U-^{238}U) at the orientations of the maximum value of thereaction cross-section increased only by **1.5 fm^2**.
- If a constant global density of value $\rho = 0.16\ fm^{-3}$is assumed in $\bar{\sigma}_{NN}(\rho, E_L / A_P)$ we found that, the reaction cross-section evaluated by this assumption is smaller, by nearly **5fm^2, 10fm^2**and **14fm^2 ,** than those calculated using the exact value of the density for the interacting pairs (^{17}N-^{17}N), (^{17}N-^{238}U) and (^{238}U-^{238}U) respectively, also except for the interacting pair (^{238}U-^{238}U) at the orientations of the maximum value of the reaction cross-section decreased only by **2.3 fm^2**.
- From Table (4), one can say that, the use of free σ_{NN} in calculating the reaction cross-section is better than using $\bar{\sigma}_{NN}(\rho = 0.16\ fm^{-3})$.

Table 2: The Values of the Reaction Cross-Section at Different Orientations for (^{17}N-^{238}U), (^{17}N-^{17}N) and (^{238}U-^{238}U) Using $\rho = \rho_P + \rho_T$

θ_p (deg.)	θ_T (deg.)	φ_p(deg.)	φ_T(deg.)	σ_R (fm^2) (^{17}N-^{238}U)	σ_R (fm^2) (^{17}N-^{17}N)	σ_R (fm^2) (^{238}U-^{238}U)
0	0	any	any	366.1	124.0	740.6
0	45	any	0	440. 3	130.6	841.6
0	45	any	60	380.4	125.0	763.6
0	90	any	0	500.2	136.8	914.5
0	90	any	30	463.1	133.1	873.9
0	90	any	45	426.6	129.4	829.2
0	90	any	90	354.6	122.2	729.3
90	90	0	0	525.7	149.9	1013.1
90	90	0	60	413.0	138.5	947.5
90	90	60	0	504.9	138.5	947.5
90	90	60	60	392.2	127.1	805.5
90	90	90	0	497.8	134.7	902.5
90	90	90	60	389.6	124.1	773.6
90	90	90	90	353.5	120.6	721.1
45	45	0	0	452.8	137.2	936. 3
45	45	0	30	432.7	135.3	914.5
45	45	0	45	412.5	133.4	890.4
45	45	0	90	371.4	129.6	835.2
45	45	0	0	452.8	137.2	936. 3
45	45	30	0	449.4	135.3	914.5
45	45	45	0	446.0	133.4	890.4
45	45	90	0	439.2	129.6	835.2

Table 3: The Maximum and Minimum Values of the Reaction Cross-Section at Different Values of E_L / A_P for (^{17}N-^{17}N), (^{17}N-^{238}U) and (^{238}U-^{238}U), Using $\rho = \rho_P + \rho_T$

E_L / A_P MeV	(^{17}N-^{17}N)		(^{17}N-^{238}U)		(^{238}U-^{238}U)	
	$\sigma_R^{max.}$ fm^2	$\sigma_R^{min.}$ fm^2	$\sigma_R^{max.}$ fm^2	$\sigma_R^{min.}$ fm^2	$\sigma_R^{max.}$ fm^2	$\sigma_R^{min.}$ fm^2
100	149.9	120.6	525.7	353.5	1013.1	721.1
200	132.2	105.5	493.0	327.9	1003.0	686.3
300	130.6	104.1	490.0	325.5	1001.7	683.2
400	133.0	106.1	494.4	328.9	1003.7	687.9
500	136.0	108.6	500.0	333.3	1005.9	693.8
600	138.8	111.0	505.2	337.3	1007.8	699.4

Table 4: The Values of the Reaction Cross-Section at Different Orientations for (^{17}N-^{17}N), (^{17}N-^{238}U) and (^{238}U-^{238}U), Using $\rho = 0\ fm^{-3}$, $\rho = 0.16\ fm^{-3}$ and $\rho = \rho_P + \rho_T$

θ_P	Three approaches	0	0	0	90	90	45
θ_T		0	45	90	90	90	45
ϕ_P		0	0	0	0	90	0
ϕ_T		0	0	0	0	90	0
σ_R (fm^2) (^{17}N-^{17}N)	$\rho = 0\ fm^{-3}$	127.4	134.2	140.6	154.2	124.1	141.1
	$\rho = 0.16\ fm^{-3}$	119.3	125.8	131.9	144.8	116.0	132.3
	$\rho = \rho_P + \rho_T$	124.0	130.6	136.8	149.9	120.6	137.2
σ_R (fm^2) (^{17}N-^{238}U)	$\rho = 0\ fm^{-3}$	370.6	445.7	506.1	532.1	358.3	458.4
	$\rho = 0.16\ fm^{-3}$	356.9	430.3	489.5	514.6	344.5	442.6
	$\rho = \rho_P + \rho_T$	366.1	440.3	500.2	525.7	353.5	452.8
σ_R (fm^2) (^{238}U-^{238}U)	$\rho = 0\ fm^{-3}$	745.4	847.0	919.8	1014.5	726.2	941.6
	$\rho = 0.16\ fm^{-3}$	726.7	827.6	901.5	1010.8	707.3	924.4
	$\rho = \rho_P + \rho_T$	740.6	841.6	914.5	1013.1	721.1	936.3

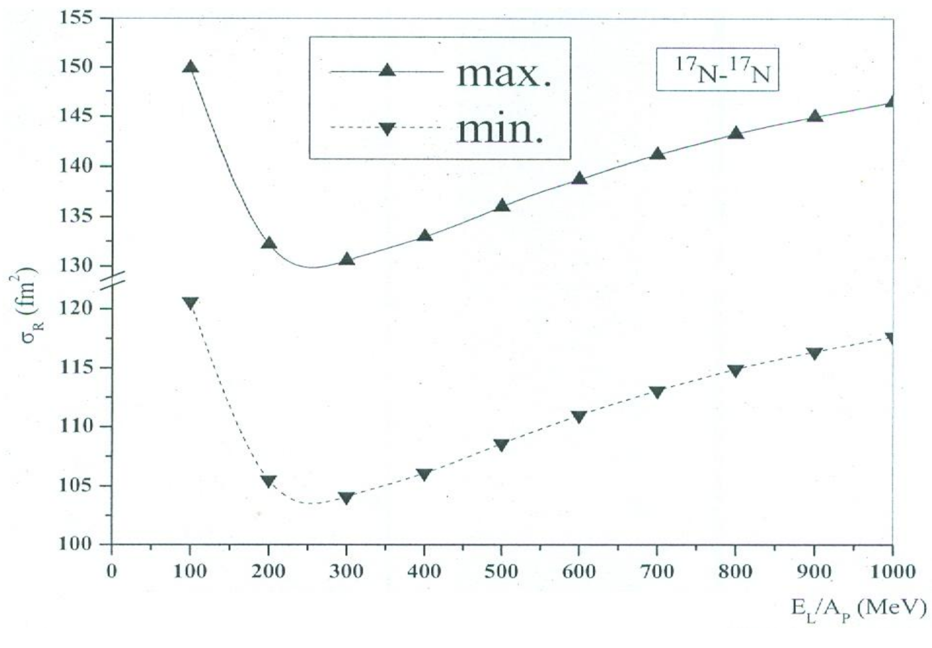

Figure 1a: The Varaition of the Reaction Cross-Section with the Energy. Max. (θ_P= θ_T=90° and ϕ_P= ϕ_T=0°), Min. (θ_P= θ_T=90° and ϕ_P= ϕ_T=90°)

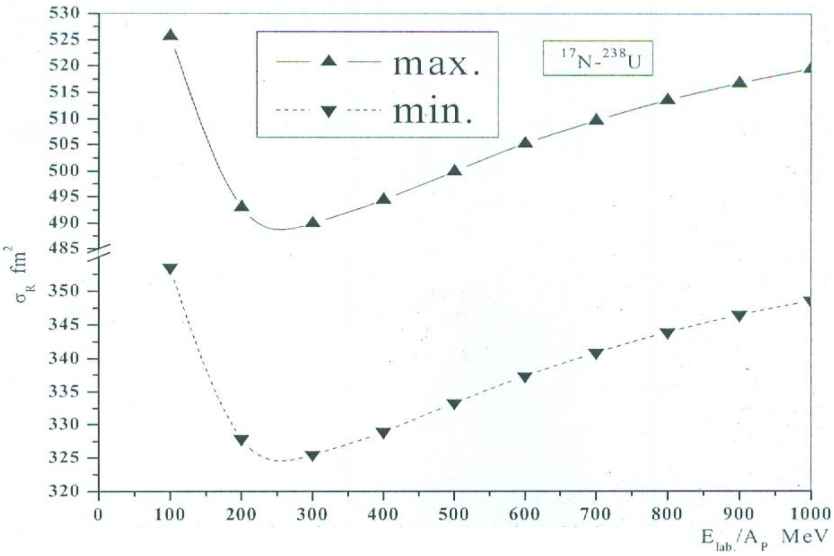

Figure 1b: The Varaition of the Reaction Cross-Section with the Energy.
Max. ($\theta_P = \theta_T$=90° and $\phi_P = \phi_T$=0°), Min. ($\theta_P = \theta_T$=90° and $\phi_P = \phi_T$=90°)

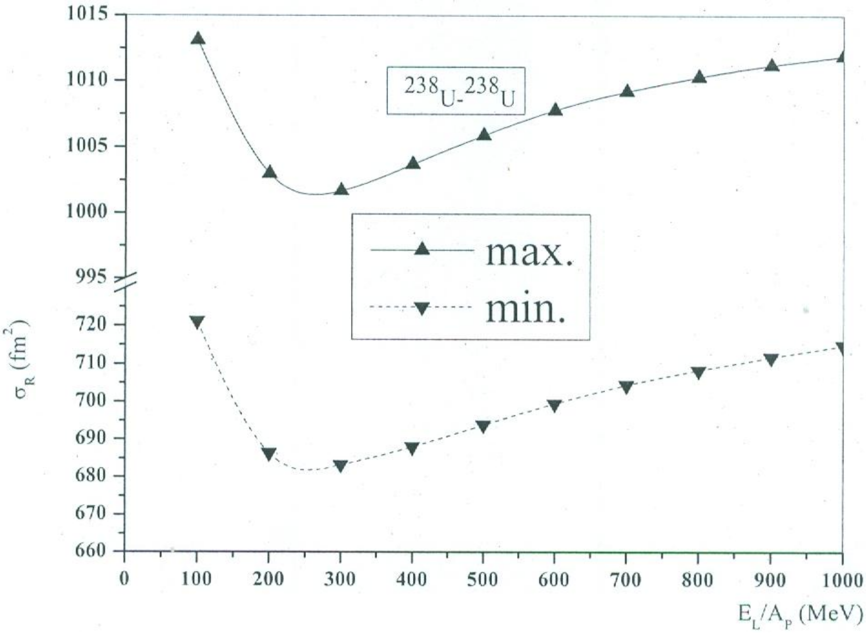

Figure 1c: The Varaition of the Reaction Cross-Section with the Energy.
Max. ($\theta_P = \theta_T$=90° and $\phi_P = \phi_T$=0°), Min. ($\theta_P = \theta_T$=90° and $\phi_P = \phi_T$=90°)

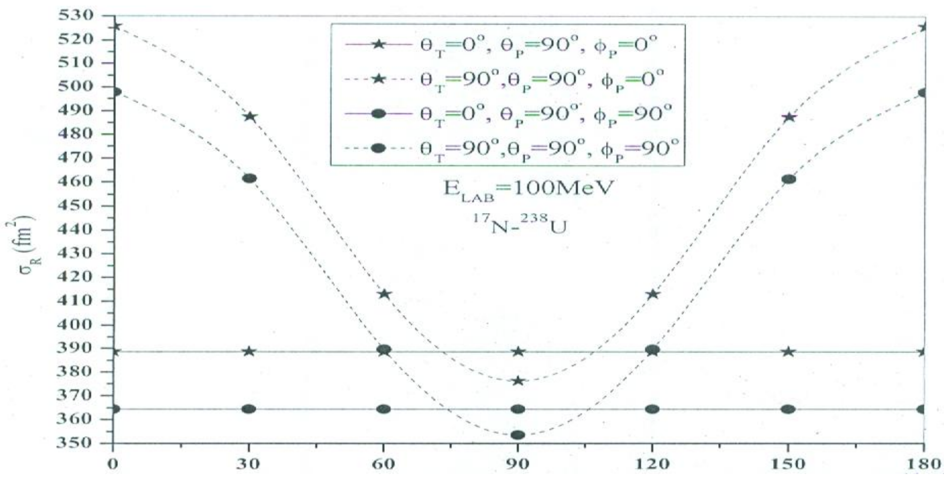

Figure 2: The Varaition of the Reaction Cross-Section with the Target Orientation $\theta_T = \theta_T$=(deg)

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